Investigating Leachate Transport at Landfill Site Using HYDRUS-1D

A. H. M. Faisal Anwar and Larissa Chan Thien

***Abstract*—Landfill leachate is a very common environmental problem that might contaminate underlying soil and groundwater. This paper investigates the potential leachate of heavy metals from the landfill site of Rottnest Island in Western Australia. The heavy metals selected for this study was Copper and Zinc as high concentration of these metals was found in Rottnest groundwater. The migration of heavy metal leachate through the soil profile was modelled using HYDRUS-1D. The model was developed for site specific conditions of Rottnest Island landfill site for the period 1996-2010 for different soil-water-chemical interaction parameters. The results show that the adsorption coefficient k_d (cm^3/g) is the most significant parameter that dominates the heavy metal migration in soil. The initial concentration also shows significant effect on leachate contamination. The longitudinal dispersion was found with moderate significance in solute transport but diffusion coefficient has no effect on contaminant migration in soil. However, initial soil moisture and saturated hydraulic conductivity showed minimum effect on leachate transport in this landfill site.**

***Index Terms*—Landfill site, heavy metals, leachate, contamination, soil.**

I. Introduction

Environmental protection for leachate control has become an increasingly important towards sustainable management of solid waste. Due to the increased population globally, the generation of solid waste has also increased significantly. Every day, a large amount of solid wastes are generated due to human activities which are either typically landfilled or incinerated. The later includes burning of solid waste. Releases of heavy metals to the environment may occur by volatilization in incineration, or in the event of fires at landfills, transfer station and recycled centers or via landfill leachate [1]. Although land filling is one of the most common method of solid waste disposal in many countries, but it has high risk in polluting the underlying soil and groundwater if the landfill site is not controlled and designed properly. That is why, it is important to monitor the leachate transport underneath the landfill on timely manner. The rate of contaminant migration depends on the physical, chemical and biological processes in the soil profile and the nature of the contaminant disposed at the landfill [2]-[5]. The contaminants (e.g. heavy metals) releasing on ground surface flow down through the unsaturated zone and penetrate into the groundwater. This has led to rapid development of analytical and technological tools to understand the transportation of landfill leachate in soil for the prediction of potential contaminant concentration in groundwater. There are various mathematical models used for this purpose such as, analytical or numerical techniques [6], [7]. Numerical models provide adaptability and capability for complicated field conditions. Simulating contaminant transport in soil by the use of mathematical model shows a better way of solving environmental issues because it provides realistic measures [8], [9]. The primary objective of this paper is to investigate the migration of landfill leachate and the concentration of leachate constituent through a soil profile of Rottnest Island using a mathematical model HYDRUS-1D.

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The authors are with the Department of Civil Engineering at Curtin University, Perth Western Australia (e-mail: f.anwar@curtin.edu.au).

II. Site Characteristics

A. Rottnest Island

The landfill site at Rottnest Island in Western Australia was selected as the study area for this research. Rottnest Island is a popular recreation island, located at latitude 32.002 °S and longitude 115.517 °E on the southwest coast of Western Australia, 18 km west of Fremantle. It is an A-class reserve of 2000 hectares of which 10% is made up of salt lakes [10]. The island is mainly built out of thick layers of Tamala limestone, a medium to coarse - medium-grained calcarenite, overlain by thin layer of the Herschell limestone and safety bay sands. The average annual rainfall on the island is 704mm.

B. Landfill Site

The biggest constraint to the waste management at Rottnest Island is its remote geographical location, 18km away from the mainland in the Indian Ocean. The island established a landfill site of 2 hectares located approximately 1.2 km west of the main settlement area in 1992 to dispose a series of waste including mixed municipal waste, food waste, bio-solids, cardboard, paper and construction waste. It was an unlined landfill and its first cell was capped in 1996 and the second cell was capped in 2002. Unlined landfill site can easily cause leachate migration from the landfill during rain events and can contaminate underlying groundwater. Department of Environmental Protection hence decided to stop the option of cutting the fourth cell and closed the site for further disposal in 2005.

C. Groundwater Quality

The main freshwater resources at Rottnest Island are the two shallow unconfined aquifers known as Oliver Hill and Wadjemup mounds. These aquifers are linked with nearby salt lakes and that is why the groundwater near lakes found with high salinity known as brackish water. Boreholes with depth of average 14m are set up around the landfill site for groundwater monitoring. The groundwater sampling from

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the boreholes showed that there are heavy metals concentrations exceeding the guidelines given by ANZECC for fresh and marine water quality [11]. For example, maximum copper and zinc concentration in landfill groundwater was found 0.015mg/L and 0.062mg/L [12]. But the maximum permissible limit for Copper and Zinc concentration are 0.0014 mg/L and 0.008 mg/L respectively in ANZECC guidelines [11]. For this reason, the transport of Copper and Zinc was considered in this study.

III. Hydrus 1D Model

The HYDRUS 1D is a one dimensional finite-element model that simulates the movement of water, heat and multiple solutes in variably saturated conditions [13]. The water movement in soil is modelled by Richard's equation:

$$\frac{\delta\theta}{\delta t} = \frac{\delta}{\delta x}\left[K\left(\frac{\delta h}{\delta x} - \cos\alpha\right)\right] \quad (1)$$

where, h is the hydraulic potential of water or water pressure head (L) which is the summation of suction head and gravity head, the θ represents the volumetric water content, t is the time, x is the spatial coordinate (L) with upwards as positive, α is the angle between the flow direction and the vertical axis (for example, $\alpha = 0°$ for vertical flow, 90° for horizontal flow, and $0° < \alpha < 90°$ for inclined flow) and K is the unsaturated hydraulic conductivity (m/day).

The Fickian's Advection-Dispersion equation used for the solute transport in the model is:

$$\frac{\delta c}{\delta t} = D\frac{\delta^2 c}{\delta x^2} - v\frac{\delta c}{\delta x} \quad (2)$$

where c is the concentration of the solute (ML^{-3}), x is the depth of the soil (L), t is the time taken for the transportation between the soil surface and the depth (T), D represents the hydrodynamic dispersion coefficient of the solute (L^2T^{-1}) and v is the velocity of the travelling solute (MT^{-1}).

The two governing equations are solved using the Crank-Nicholson implicit scheme for time weighting scheme and Galerkin finite elements for the space weighting scheme.

IV. Model Parameters

The initial water content, θ of the soil profile is set at 0.1 (default setting) for 14m depth of soil profile. The initial concentrations of both heavy metals are set at 100mg/L and 10g/L respectively for two types of simulations. The upper boundary condition is set as an 'Atmospheric boundary' with surface runoff. The lower boundary condition is considered to be a free drainage for a landfill site. However, the model was run for 15 years (1996-2010) with Rottnest Island mean monthly precipitation records (n=179). For limestone, the bulk density values ranges from 1.3-2.6 g/cm^3 depending on the form of the limestone. The average bulk density for most limestone is taken as 1.5 g/cm^3 and therefore, it is left at the default setting of 1.5g/cm^3. The leaching potential was evaluated under the soil type of limestone and the Van Genuchtan soil hydraulic properties are shown in Table I. The soil distribution coefficient or adsorption coefficient k_d, is a measure of the chemicals ability to leach and the final concentration of the leachate through the groundwater. For this reason, it is very important to investigate the effects of interaction between soil and the heavy metals by varying k_d values. The value of k_d was set for Copper and Zinc at 4.0×10^{-5} m^3/g and 1.6×10^{-5} m^3/g respectively. The diffusion coefficients, D_W of Copper and Zinc in free water were considered zero.

TABLE I: The Van Genuchten Hydraulic Parameters for Soil

Material Type	Θ_r (%)	Θ_s (%)	α (m^{-1})	N	K_s (m/day)	Reference
Tamala Limestone	0	11	0.0365	1.83	86.4	Roulier, *et al.* [14]

V. Results and Discussion

A. Effect of Initial Concentration

In order to check the effect of initial concentration on leachate migration, modelling was performed for two initial concentrations (e.g. 10g/L and 100mg/L) for selected heavy metals (Copper and Zinc). The observation nodes (N1-N8) were considered at 1m, 2m, 4m, 6m, 8m, 10m, 12m, and 14m depth along the soil profile. The simulation results are shown in Fig. 1 (a and b) and Fig. 2 (a and b) respectively for two initial concentrations.

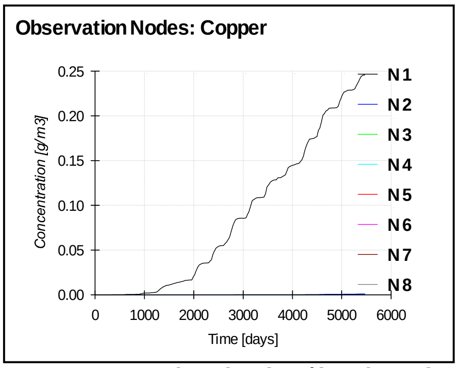

Fig. 1a. Copper concentrations through soil profile with initial concentration of 10g/L.

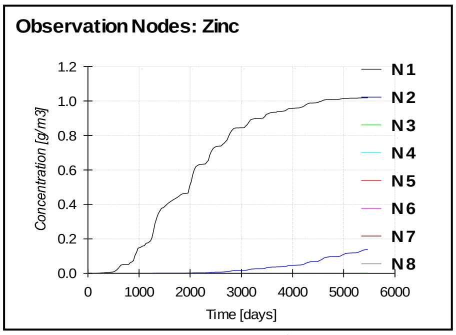

Fig. 1b. Zinc concentrations through soil profile with initial concentration of 10g/L.

The results revealed that the Zinc concentration was found much higher than the Copper concentration in soil. The copper leachate reached 1m depth after the end of third year and it has a concentration of 0.00245 mg/L after 15 years (end of modelling period) when initial concentration was considered 10g/L. For the same initial concentration of 10g/L, the Zinc leachate reached at 1m depth after 15 years with a concentration of 0.0102 mg/L and entered at 2m depth after 7 years. The accumulated Zinc concentration was found to be 0.0016 mg/L after the end of 15 years. The similar nature of heavy metal migration was obtained with the initial concentration of 100mg/L for both heavy metals but concentration in soil was found 100 times less with a 10 times less initial concentration. This indicates lower concentration of heavy metal leachate from landfill site will have significantly lower possibility of leaching through the soil. However, these values were found less than the maximum permissible value of these metals given in ANZECC guidelines [11].

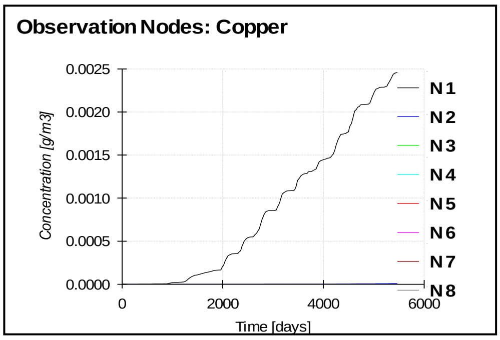

Fig. 2a. Copper concentrations through soil profile with initial concentration of 100mg/L.

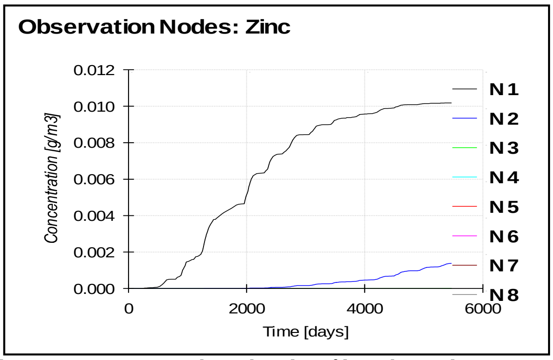

Fig. 2b. Zinc concentrations through soil profile with initial concentration of 100mg/L.

B. *Effects of Adsorption Coefficient, k_d*

The soil adsorption coefficient k_d significantly affects the final concentration of heavy metals in soil. The model was run at default parameters for landfill site but k_d values were varied as shown in Table II.

TABLE II: SUMMARY OF K_D VALUE USED AS INPUT IN HYDRUS 1D

Heavy Metals	k_d value (m^3/g)			
Copper	4.0×10^{-5}	4.0×10^{-7}	4.0×10^{-9}	0
Zinc	1.6×10^{-5}	1.6×10^{-7}	1.6×10^{-9}	0

How leachates are migrated in soil profile for different k_d values (k_d=4.0×10^{-7} and k_d=4.0×10^{-9}) are shown in Fig. 3 and 4 for Coper and Zinc respectively. This showed that the adsorption coefficient is one of the most important factors influencing the migration of the leachate through the soil profile. Smaller the adsorption coefficient of solutes in soil, the lesser is the solute adsorbed by the soil and hence, the leachate speed increases as the k_d value decreases. This showed that under the default k_d value in the decimal place of 10^{-5} m^3/g there are heavy metal leachate being adsorbed into the tamala limestone and therefore, are unable to contaminate the groundwater at the depth of 14m profile.

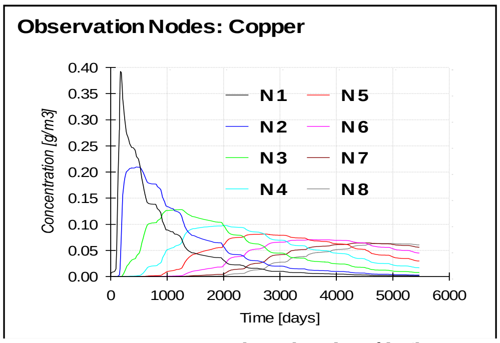

Fig. 3a. Copper concentrations through soil profile (k_d=4.0×10^{-7}).

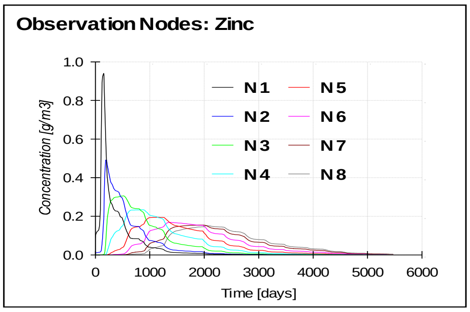

Fig. 3b. Zinc Concentrations through soil profile (k_d=4.0×10^{-7}).

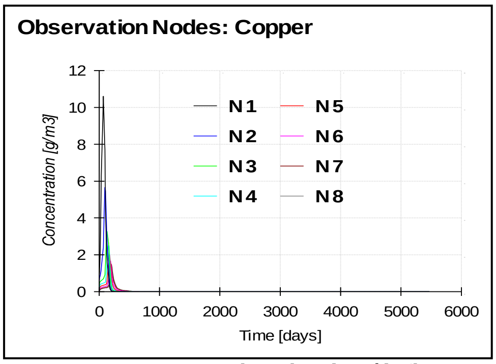

Fig. 4a. Copper concentrations through soil profile (k_d=4.0×10^{-9}).

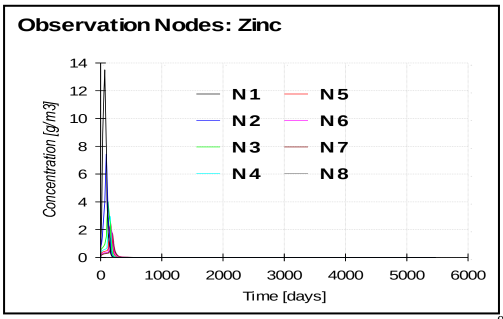

Fig. 4b. Zinc concentrations through soil profile (k_d=4.0×10^{-9}).

The only possibility of reaching the leachate at bottom of the soil profile is if the k_d value is 100 times smaller (e.g. k_d=4.0×10^{-9} as shown in Fig. 4a and 4b*)*. The actual k_d value of tamala limestone for heavy metals may in fact be much lower than the k_d values obtained from average tests on general soil. This may be the reason why few heavy metal concentrations in groundwater were found exceeding the ANZECC guidelines [11]. This revealed that the initial concentration of 100mg/L can be dangerous if the absorption coefficient of the particles is very low and allow the particles to leach into the groundwater. The results obtained for the k_d values with decimal place of 10^{-9} and 0 can said to be almost identical. When k_d=0, that means heavy metals are not adsorbed by the soil and it may directly leach to groundwater.

Again, from the nature of the graphs, it is revealed that the leachate migration of two heavy metals studied in this research have similar characteristics.

C. Effects of Longitudinal Dispersivity, D_L

To investigate the effects of longitudinal dispersivity (D_L), the value of D_L was varied 0.1-1m. This parameter is considered one of the controlling factors of heavy metals leachate as it provides the mechanical mixing in solute transport. The result revealed that the Copper leachate migration to 1m depth decreased from 4th year to 7th year by about 26% of its default condition. At the end of 15 years, 99.5% concentration reduction was observed at this depth for Copper. For Zinc leachate to reach at this depth of 1m, time took about 1.5 years. 27% of zinc reduction was observed after 5.5 years whereas 76.5% reduction was observed at the end of 15 years at this depth.

D. Effect of Initial Water Content, θ

The initial water contents were varied between 0 - 0.1. The result showed that there were only relatively small changes in the concentration of the heavy metals at the 1m depth through the soil profile and proved that the effect of initial moisture content has very little impact in this model of heavy metals leachate. The reduction of concentration of heavy metals in soil is not a function of initial water content.

E. Saturated Hydraulic Conductivity, K_s

This section of the paper discusses the effects of saturated hydraulic conductivity on landfill leachate transport. The K_s values were taken in the range of 10-1000 m/day. The results revealed that leachate transport of Copper or Zinc did not have significant effect on the saturated hydraulic conductivity of the soil.

F. Effect of Diffusion Coefficient in Water, D_w

The effect of D_w was checked using the Diffusion Coefficient in fresh water and sea water respectively. The diffusion coefficient of heavy metals in sea water was considered because Rottnest Island is a unique site with hypersaline lakes and high saline groundwater. The value of D_w in sea water for Copper and Zinc are taken as 6.33×10^{-5} m^2/day and 6.18×10^{-5} m^2/day respectively [15]. The results were found identical to Fig. 1a and 1b indicating that there is no effect on diffusion coefficient on leachate transport in soil.

Though the heavy metals concentration of Copper and Zinc in Rottnest groundwater (from boreholes samples near landfill sites during regular monitoring) was found exceeding the ANZECC guidelines [11], the HYDRUS-1D model results did not show significant metal pollution in groundwater from the landfill of Rottnest Island. The highest values of heavy metals were found only at a depth of 1m over a period of 15 years, which are 0.00245 mg/L for Copper and 0.0102 mg/L for Zinc which are just above the trigger value [11]. However, the ANZECC guidelines given are for freshwater and inshore marine water ecosystem [11], there is no criterion for saline groundwater. Also, the initial concentration of heavy metals deposited on the landfill site is only an estimation taken from the average values of most deposited materials. Therefore, the results presented herein provide an indication how heavy metals leachate are transported in the soil of Rottnest Island.

VI. Conclusions

The HYDRUS-1D model was used to investigate the heavy metal migration at a landfill site of Rottnest Island, Western Australia. Two heavy metals Zinc and Copper were selected for this study as these two were found in higher concentration in Rottnest groundwater. The contaminant migration of these two heavy metals were modelled for different solute transport parameters including initial concentration, soil adsorption coefficient, longitudinal dispersion, saturated hydraulic conductivity, initial soil water content and water diffusion coefficient. The results revealed that soil adsorption parameter is the most dominating factors for leachate transport in landfill site. The initial concentration also shows significant effect on mass transport in soil. The longitudinal dispersion was found affecting moderately on leachate migration but water diffusion coefficient has no effect. The initial soil moisture and saturated hydraulic conductivity shows minimum effect on leachate transport in soil. However, the values for different parameters used in this research were taken from different literatures. The actual values may be obtained from experiments using Rottnest soil and can be used in models to get more realistic results.

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A. H. M. Faisal Anwar received his PhD degree in civil engineering (environmental) from Nagoya University, Japan in 2000. Currently he is working as an associate professor in the Department of Civil Engineering at Curtin University in Western Australia. Prior to joining Curtin, he served as a lecturer, assistant professor and associate professor in the Department of Water Resources Engineering at Bangladesh University of Engineering and Technology. He also worked as a postdoctoral research fellow in the Graduate School of Environmental Sciences at Nagoya University, Japan. He is the recipient of Pro-Vice Chancellor's Teaching Excellence Award 2011, Vice-Chancellor's Teaching Excellence Award 2012 of Curtin University and a National Citation Award 2013 for outstanding contribution to student learning from the Office for Learning and Teaching, Australian Government. His research interests include groundwater and aquifer dynamics, stormwater/greywater management and climate change effect on water resources.